ANNEALING OF RADIATION DAMAGE IN LOW RESISTIVITY SILICON SOLAR CELLS

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Silicon solar cells with base resistivity of 0.1 ohm-centimeter are projected to achieve 18 percent air mass zero efficiencies (ref. 1). It has been found in the past that these low-resistivity cells require annealing temperatures of approximately 500° C to restore performance after radiation-induced degradation (ref. 2). However, if annealing in space is to become a reality, temperatures of 200° C or lower are required to prevent irreversible damage to other parts of the solar array. Hence, we have been conducting a program to reduce the temperatures required to restore cell performance after irradiation. Previous investigations into the annealing behavior of radiation-induced defects produced in p-type silicon indicate that oxygen and carbon are constituents of the major defects observed after irradiation with 1-MeV electrons (refs. 3 and 4). Hence, our current efforts are concerned with the annealing characteristics of two groups of cells containing different amounts of oxygen and carbon.

Junction formation in one group of cells was achieved by phosphorous ion implantation into 0.1-ohm-cm float-zone silicon with oxygen and carbon concentrations $<5\times10^{15}/cm^3$. The second group of cells was fabricated by phosphorous diffusion into 0.1 ohm-centimeter float-zone silicon whose oxygen and carbon concentrations were $10^{16}/cm^3$. After irradiation by 1-MeV electrons the cells were isochronally annealed, time at temperature being 20 minutes. Results for the diffused junction cells are shown in figure 1 where annealing temperatures around 500° C are indicated. The isochronal annealing data for the ion-implanted cells are shown in figure 2, where it is seen that the annealing temperatures are fluence dependent and where, at a fluence (ϕ) of $10^{14}/cm^2$, an annealing temperature of 300° C is observed. With increasing fluence, the temperature increases until, at $\phi = 3\times10^{14}/cm^2$, annealing occurs around 500° C. An additional feature of the data is the appearance of reverse annealing, which occurs at temperatures above 400° C as the fluence increases above $10^{14}/cm^2$.

The presently observed 200° reduction in annealing temperature is highly significant but not sufficient to achieve the goal of annealing at 200° C. Further reduction appears possible by identifying and removing the defects responsible for the occurrence of annealing at 300° C. The first step in this procedure is defect identification, which we attempt by considering some of the properties of known defects in p-type (boron-doped) silicon. However, because of sensitivity limitations, data from deep-level transient spectroscopy (DLTS) are not available for 0.1-ohm-centimeter boron-doped silicon. On the other hand, defect spectra from DLTS are available from previous work for 0.3-ohm-centimeter silicon (ref. 3). Figure 3 shows the DLTS data for this low resistivity boron-doped silicon,

and table I summarizes the information available on the defects shown in the figure.

Referring to table I and figure 3, the defects at $E_V + 0.48$ and $E_V + 0.26$ eV are unidentified. For the remaining defects, although identifications are available, many are ambiguous. The defect at $E_V + 0.38$ eV has been ambiguously identified as a vacancy-oxygen-carbon complex (V-O-C) (ref. 3) or a carbon-interstitial carbon-substitutional pair (C_I-C_S) (refs. 5 and 6). We note from figure 3 that the annealing temperature for this defect favors the V-O-C identification. However, the simultaneous presence of both defects below 300° C is not precluded. The defect at $E_V + 0.23$ eV with annealing temperature at 300° C has been unambiguously identified as the divacancy (refs. 3 and 5). As seen from the table, the defect at $E_C - 0.27$ eV is a boron related defect (refs. 3 and 5). It is observed that disappearance of this defect is followed by growth of the defect at $E_V + 0.30$ eV (ref. 3). This latter defect has been tentatively identified as either a boron-oxygen vacancy complex (ref. 3) or the silicon di-interstitial (ref. 5). However, from figure 3 it is seen that this defect anneals out at a temperature slightly above 400° K, while the silicon di-interstitial anneals out at 500° C (ref. 7). The preceding discussion indicates that the possible defects that anneal out at 300° C are the divacancy and the silicon di-interstitial. If these were the only significant defects present at the lower fluence, they could be responsible for the annealing observed at 300° C. This could be possible if a fluence dependence existed for the production rate of the remaining defects such that their concentration was very low at $\phi = 10^{14}/cm^2$ and increased significantly with increasing fluence. However, there is no experimental evidence to support the postulated fluence dependence. With respect to the fluence dependent reverse anneal observed between 400° and 500° C, it is difficult from the present data to assign this effect to a specific defect or defects.

The preceding consideration of defect behavior in irradiated boron-doped silicon leads to the tentative conclusion that further reduction in annealing temperature could be achieved by decreasing the carbon concentration and either neutralizing the divacancy and/or minimizing its formation as a result of irradiation. We emphasize the speculative nature of this conclusion. The fact remains, however, that the present work has demonstrated a significant reduction in the temperature required to remove radiation-induced degradation in 0.1-ohm-centimeter silicon solar cells.

REFERENCES

1. Godlewski, M. P.; Brandhorst, H. W., Jr.; and Baraona, C. R.: Effect of High Doping Levels on Silicon Solar Cell Performance. Eleventh Photovoltaic Specialists Conference - 1975, IEEE, 1975, pp. 32-35.
2. Weinberg, I.; and Swartz, C. K.: Annealing of Radiation Damage in 0.1 and 2 ohm-cm Silicon Solar Cells. NASA TP-1559, 1979.
3. Mooney, P. M.; et al.: Defect Energy Levels in Boron Doped Silicon Irradiated with 1-MeV Electrons. Phys. Rev. B, vol. 15, no. 8, Apr. 15, 1977, pp. 3836-3843.

4. Weinberg, I.; and Swartz, C, K.: Origin of Reverse Annealing in Radiation-Damaged Silicon Solar Cells. Appl. Phys. Lett., vol. 36, no. 8, Apr. 15, 1980, pp. 693-695.
5. Kimerling, L. C.: Defect States in Electron-Bombarded Silicon: Capacitance Transient Analysis. International Conference on Radiation Effects in Semiconductors, Dubrovnik, Yugoslavia, 1976, N. B. Urli and T. W. Corbett, eds. Institute of Physics (London) Conference Series no. 31, 1977, pp. 221-230.
6. Brower, K. L.: EPR of a John Teller Distorted <111> Carbon Interstitialcy in Irradiated Silicon. Phys. Rev. B, vol. 9, 1974, pp. 2607-2617.
7. Brower, K. L.: EPR of a <001> Si Interstitial Complex in Irradiated Silicon. Phys. Rev. B, vol. 14, pp. 872-883 (1976).

TABLE I. - ANNEALING AND CAPTURE CROSS SECTIONS OF MAJOR DEFECTS IN BORON-DOPED SILICON

Energy level, eV	Defect	Anneal temperature, °C		Capture cross section, cm^2		Detection method
		In	Out	σ_n	σ_p	
E + 0.38	V-O-C or C_I-C_S	30 ---	400 300	0.3×10^{-13} ---------	2×10^{-16} -------	EPR, DLTS EPR, DLTS
E_v + 0.23	Divacancy	---	300	4×10^{-13}	3×10^{-16}	EPR, DLTS
E_c - 0.27	$B_I O_I$ or B_I-B_S	--- ---	200 180	2×10^{-13} -------	------- -------	DLTS DLTS
E_v + 0.30	B-O-V or S_I-S_I	170 200	400+ 500	3.6×10^{-13} ---------	2×10^{-16} -------	DLTS EPR, DLTS
E_v + 0.26	---------	270	330	10^{-13}	-------	DLTS

FIGURE 1: - ANNEALING TEMPERATURES OBSERVED IN RADIATION DAMAGED SILICON SOLAR CELLS

(CELL P-N JUNCTION FORMED BY DIFFUSION; RESISTIVITY = 0.1 OHM-CM)

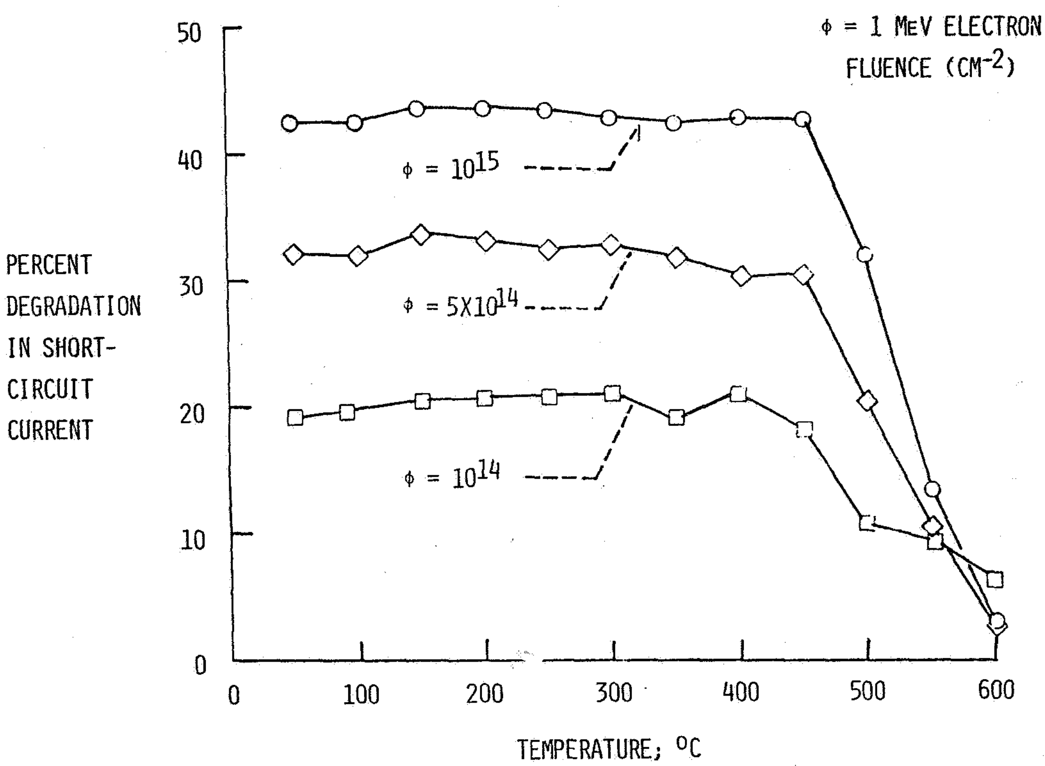

FIGURE 2: - REDUCED ANNEALING TEMPERATURES IN RADIATION DAMAGED SILICON SOLAR CELLS

(CELL P-N JUNCTION FORMED BY ION-IMPLANTATION; RESISTIVITY = 0.1 OHM-CM)

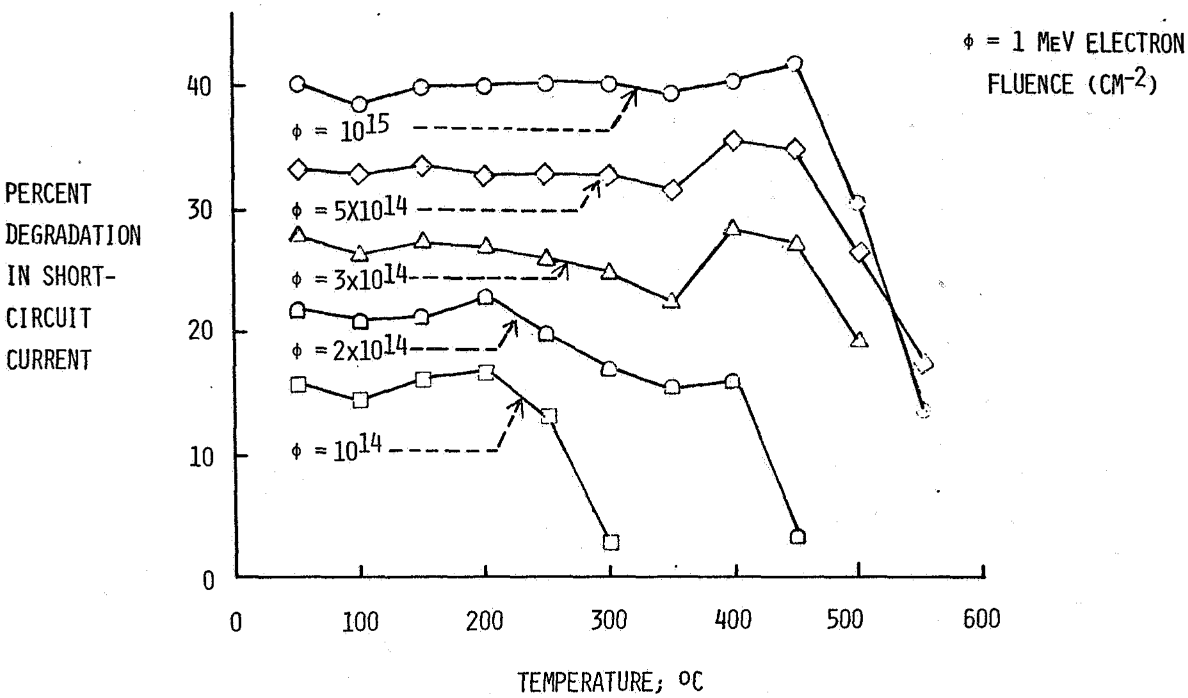

FIGURE 3: - DLTS DATA FOR 0.3 Ω-CM P-Si ISOCHRONALLY ANNEALED AFTER 1 MeV ELECTRON IRRADIATION